Profitability Study of Floating PV and Storage Pumped Hydropower Plant

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***Abstract*—This article is devoted to the problems of management and profitability of large-scale hybrid photovoltaic and pumped storage power plants. The decision-making methodology for substantiating the taxation is proposed. An optimisation problem is solved. The rationality of changing the rules of payment for transmission grid services is shown. Based on long-term forecasts of photovoltaic generation and changes in electricity market prices, the NPV of the cash flow is estimated and the acceptable time of return on investment is proved. The economic indicators of the technologies under consideration and distributed small photovoltaic plants are compared.**

Index Terms-- renewable energy; pumped storage hydropower plant, electricity market; floating photovoltaic plant; optimisation

I. Introduction

The large-scale use of renewable energy sources is an important and necessary step towards the limitation of greenhouse gas emissions into the atmosphere and climate change mitigation. Nevertheless, a further increase in the use of these energy sources is associated with the need to solve a number of serious problems. Particularly, the placement of sources of generation is often associated with the need to use land plots of significant area. Floating photovoltaic (FPV) technology located in the reservoir of a pumped storage hydropower plant (PSHPP) is one of possible solutions to mitigate this problem. PSHPPs are equipped with two reservoirs connected by a downtake of a large diameter through a reversible pump-turbine unit which allows to use the potential energy accumulated in the upper reservoir to generate electricity. The reservoirs of PSHPPs occupy large areas and can be used to house FPV technology. The use of two technologies in combination with their management that takes into account the conditions of the energy market provides the possibility of balancing generation and consumption, does not require a land plot for FPV and is attractive according to economic criteria.

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A significant amount of research has been devoted to the opportunities and challenges associated with the widespread deployment of FPV installations [1-2]. FPV systems have significant advantages versus ground-mounted PV systems: zero land costs (no land occupancy), minor grid connection costs and enhanced availability to the existing networks, an increased efficiency coefficient. The potential of FPV is vast [3]. For instance, according to results presented in [3], the potentiality of power production from FPV is estimated at 3,401 reservoirs. The annual power production was estimated to be 2,932 GWh, and the annual reduction amount in CO_2 emissions will be approximately 1,294,450 tonnes.

FPVs can be combined with both hydroelectric power stations (HPPs) and PSHPPs, creating powerful hybrid energy-generating systems [4-6]. Such systems cause a new renewable energy market to meet the ever-growing demand, respond to peak loads, increase economic profits, solve environmental problems, etc.

Number of papers are dedicated to FPV/PV synergy with PSHPP [7, 8]. Several publications [9, 10] underline the importance of analyzing the technical and economic aspects of FPV systems: an energy saving calculation, water saving estimation, a calculation for reduction in CO_2 emissions and the payback period. A number of scientific publications investigate optimal scheduling models of PSHPP operation [11-13]. In [12], the authors formulate the optimisation task as a mixed integer problem. A model for optimising operation of the hybrid PV power and a PSHPP (PV-PSHPP) is offered in [14].

Each country has different components forming the electricity end price: taxes, support payments, electricity transmission tariffs. Last mentioned, namely electricity transmission tariffs are used to reimburse the costs of the provision of electricity transmission services. At the international level, there are many different pricing systems for electricity transmission and associated tariff structures [15].

Summarising the results of publications on various types of hybrid plants, including FPV systems and PSHPPs, we can note the following: evidence of the possibilities and advantages of the combined use of solar and hydraulic energy; the presence of models and algorithms for optimal control of the process of energy storage and generation; the possibility of implementing cost-effective, large-scale projects for the construction of FPV systems in artificial reservoirs of existing PSHPPs; the dependence of project profitability on solar irradiation, parameters of hydroelectric power plants, electricity market prices and taxation rules for generation or consumption. Tax rules manage the relationship of generating companies, power grids and consumers and are adopted by decisions of government agencies. These decisions can accelerate or slow down the development of energy sectors. However, to our knowledge, there are no studies supporting the taxation of hybrid stations of the type in question.

The main contributions of the article are as follows: decision-making technology for substantiating the taxation of a hybrid plant is proposed and developed. An optimisation problem has been posed and solved including maximising the profit of the coalition of a station and a transmission grid; the rationality of changing the rules of payment for transmission grid services is shown; the tasks of maximizing and distributing the additional gain of the coalition are posed and based on the use of the Shapley value, they are solved.

The rest of the article is organised as follows: Section 2 describes FPV-PSHPP technical issues and the formulation of the problem. Objective functions, state and decision variables, constraints, procedures for forecasting the prices are presented in Section 3. Moreover, Section 3 is devoted to a specific study of the profitability of a real-life powerful PSHPP and a planned FPV plant located in the reservoir of the PSHPP. The key conclusions are summarized in Section 4.

II. MATERIALS AND METHODOLOGY

The structure of the energy system accepted for consideration includes the following main objects: pumping hydropower plant, the reservoir of which can be used for the construction of a FPV; the transmission grid to which the PSHPP is connected and through which the flows of generated and consumed energy circulate; the electricity market, according to the rules of which the generation and consumption of energy are controlled; government agencies establishing taxation rules for energy producers and consumers.

We assume that the station, the grids (“Participants”) strive to increase their profitability, but are forced to follow the technical and legal constraints established by the laws of physics, the market, the government and the networks. The system in question is controllable. Solar energy can be given to the network or used to accumulate energy in the reservoir. Units of the pumping plant can be set to the generation or pumping mode. The government can choose energy billing rules. An important feature of the system under consideration is the presence of several decision-makers. The decision-making methodology can be created on the basis of setting and solving the optimal control problem [16] which include the rules of billing considering market prices (state variables), as well as additional taxes and fees that take into account the interests of electric networks and the state. Energy pricing rules are drafted by government agencies. There is a wide variety of account generation rules [15, 17]. The problem of optimising the scheduling of the charge/discharge of FPV-PSHPP makes sense only if dynamic billing systems are used that take into account hourly price changes and schedule of energy generation or consumption. Such a system usually consists of three components. The first is proportional to the energy market price at a given hour. The second component is proportional to the energy consumed or generated (without taking into account the market price). This component includes the sum of additional payments $P_{r\,add}$ such as: trade commission; electricity distribution fee, mandatory procurement component. The third component is a fixed one, which depends on the capacity value (a capacity-based connection fee); the mandatory procurement component for the connection. The billing rule, taking into account the presence of the named components, can be written down in the following form:

$$C^t = k_m \cdot P^t_{r\,mark} \cdot W^t + k_f \cdot P^t_{r\,add} \cdot W^t + P_{fix}\,, \quad (1)$$

where C^t — the total costs of the end-user for the electricity bill at hour t, €; W^t — the consumed or generated energy at hour t, MWh; $P^t_{r\,mark}$ — the electricity market price at hour t, €/MWh; $P^t_{r\,add}$ — additional variable components of the billing system without the electricity market price at hour t, €/MWh; k_m and k_f — proportionality coefficients; P_{fix} — fixed component of electricity bill for the end-user, €/MW/hour.

The freedom to choose k_m, k_f and P_{fix} is limited by government agencies. In Europe [17] the unit transmission tariff (UTT) is applied to generation and load in 16 countries whereas in 20 countries only load is charged. The average level of the transmission system operator’s (TSO) part of the UTT is 8.23 €/MWh for load and 0.52 €/MWh for generators.

When solving the problem under consideration there are complications caused by the presence of several decision makers. Overcoming these difficulties is possible through the use of elements of the theory of cooperative games, in particular through the application of the Shapley distribution [18]. In the game theory, the Shepley value [18, 19] describes one approach for fairly distributing the benefits obtained by forming a coalition. In this article we will need the simplest option, considering a coalition of two players. In this case, according to Shapley, the additional profit is divided equally. As a result of the distribution of extra winnings, each player receives a half of the total profit, which compensates for additional expenses and takes into account the contribution of each participant to the creation of additional benefits [18].

III. CASE STUDY AND RESULTS

Object under review

The powerful PSHPP actually existing in Lithuania [20], which is supposed to be supplemented by a FPV station is taken as object under review. Parameters of FPV-PSHPP are presented in Table 1. We accept that the hypothetical station is a participant of the Nord Pool day a head electricity market.

TABLE I FPV-PSHPP PLANT PARAMETERS

Name of parameter;Unit of measurement	Value
Upper reservoir area, km^2	3.05
Maximal water head, m	113.5
Minimal water head, m	105.5

Number of reversible pump-turbine units K, pcs	4
Rated capacity in generation mode, MWh/h	225.0
Rated capacity in pumping mode, MWh/h	220.0
Efficiency in generation/ pumping mode, %	90.0 / 80.0
Rated capacity of FPV, MW	250
Total pool capacity, m^3	48,000,000

The station is connected to a powerful transmission grid (330 kV), which does not impose restrictions when choosing stations operating modes.

When planning the operation, we accept: that the water levels in the upper reservoir at the beginning and at the end of the planning period are equal to the maximum permissible and that the pump-turbine units at each hour can work only with rated power and that the combination of the generation mode and the pumping mode is impossible. The use of solar energy is completely dependent on the mode of the PSHPP: if this plant is operating in a generator or in a passive state, then the solar energy is transferred to the grid; if pumping mode is selected, then solar energy is used on site, reducing energy consumption from the grid. Rated FPV capacity (250 MW) corresponds to the area of the upper reservoir (3,000,000 m^2).

Objective functions and constrains

To increase the visibility, we formulate the goals of the participants for the station containing only one turbine unit. In the case of several aggregates, the number of Boolean variables increases in proportion to the number of aggregates, however, these changes do not cause fundamental complications. Given the assumptions made, the task of maximising the incomes of FPV-PSHPP ($I^*_{FPV-PSHPP}$) can be written in the following form:

$$I^*_{FPV-PSHPP} = E(\sum_{t=1}^{T_{pl}} P^t_{gen} \cdot \tau \cdot \eta_{gen} \cdot (P^t_{r\,mark}) \cdot \beta^t_{gen} + P^t_{FPV} \cdot \tau \cdot (P^t_{r\,mark}) \cdot \beta^t_{FPV,g} - P^t_{pump} \cdot \tau \cdot \frac{1}{\eta_{pump}} \cdot (P^t_{r\,mark} + P_{tran}) \cdot \beta^t_{pump} + P^t_{FPV} \cdot \tau \cdot (P^t_{r\,mark} + P_{tran}) \cdot \beta^t_{FPV,p}) \rightarrow max \quad (2)$$

$$I^*_{TSO} = \sum_{t=1}^{T_{pl}} P^t_{pump} \cdot \tau \cdot \frac{1}{\eta_{pump}} \cdot (P^t_{r\,mark} + P_{tran}) \cdot \beta^t_{pump} - P^t_{FPV} \cdot \tau \cdot (P^t_{r\,mark} + P_{tran})\, \beta^t_{FPV,p} \rightarrow max \quad (3)$$

where P^t_{gen} — the unit's operational range in generator mode at *t*-th hour, MW; τ — sampling step (one hour); η_{gen} — efficiency coefficient in generator mode; β^t_{gen} — boolean value in generator mode; P^t_{FPV} — amount of generated energy from FPV at *t*-th hour, MW; $\beta^t_{FPV,g}$ — boolean value for sale to the grid; P^t_{pump} —the unit's fixed capacity in pump mode at *t*-th hour, MW; η_{pump} — efficiency coefficient in pump mode; P_{tran} —electricity transmission tariff, €/MWh; β^t_{pump} — boolean value in pump mode; $\beta^t_{FPV,p}$ — boolean value for energy compensation in pump mode.

Note that (3), which represents the interests of the TSO, contains only one decision variable (P_{tran}) that it can select; (2) contains the same variable, but it is chosen not by the revenue maximizing decision maker (FPV-PSHP), but by the TSO. The objectives of these decision makers do not coincide, therefore, the equations cannot be directly used to solve the problem under consideration. In addition, in both equations we can see the multiplications of the decision variables P_{tran}, β^t_{pump}, β^t_{gen}, $\beta^t_{FPV,p}$, $\beta^t_{FPV,g}$ so the maximization procedures cannot be implemented using Integer linear programming. Both of these complications are usually overcome by assigning a fixed P_{tran}, the value of which has assigned by decision of government agencies. We choose a different path, considering that P_{tran} is a hidden variable, the value of which is to be preferred. To do this, it is necessary to solve the problem of maximizing coalition revenues, I^*_{coal}, which can be written as follows:

$$I^*_{coal} = I^*_{FPV-PSHPP} + I^*_{TSO} \rightarrow max \quad (4)$$

If the condition: $I^*_{coal} > I^*_{FPV-PSHPP} + I^*_{TSO}$ is satisfied, then a coalition is possible. It remains to evaluate the benefit and distribute them to the players. In this case, the whole problem solving algorithm contains the following steps:

· Evaluation of the maximum profit of the FPV-PSHPP and TSO for P_{tran} given by decision of government (without forming a coalition).

· Determining the amount of additional profit and its distribution to both participants.

Note that a coalition can be formed and its work optimized using (4) even in the absence of a FPV station. Suppose that such an optimization has been carried out and an estimate has been obtained of the coalition's profit without the participation of the Floating Station. Comparing two optimisation results (with FPV and opposite), it is easy to estimate the additional profit, P_{add}, created by the floating station:

$$P_{add} = I^*_{coal} - I^*_{coal-FPV} \rightarrow max \quad (5)$$

where $I^*_{coal-FPV}$ — the profit of a coalition operating without the participation of FPV station, €

The solution of the problems (2), (3) and (4) should be carried out taking into account the constraints as follow:

$$\begin{cases} H_{min} \le \sum_{t=1}^{T_{pl}} \left(H_{init} + \sum_{n=1}^{N} H_{dis} \cdot (-\beta^{n,t}_{gen} + \beta^{n,t}_{pump}) \right) \le H_{max}, \\ \sum_{t=1}^{T_{pl}} \sum_{n=1}^{N} H_{\Delta} \cdot (-\beta^{n,t}_{gen} + \beta^{n,t}_{pump}) = H_{init} - H_{final} \\ \beta^t_{FPV,g} + \beta^t_{FPV,p} \le 1, \forall t \in T \\ \beta^t_{FPV,p} = \beta^{n,t}_{pump}, \forall t \in T, \forall n \in N \\ \beta^{n,t}_{gen} + \beta^{n,t}_{pump} \le 1, \forall t \in T, \forall n \in N \end{cases} \quad (6)$$

where H_{Δ} — a water discharge/charge during operation of one unit for 1 hour in order to generate maximal power or pump with maximal capacity respectively, m; H_{min} — minimal water level of Kruonis PSHPP reservoir, m; H_{max} — maximal water level of Kruonis PSHPP reservoir, m; H_{init} — initial water level of Kruonis PSHPP reservoir, m; H_{final} — final water level of Kruonis PSHPP reservoir, m; N — total number of generation units; n — index of generation unit.

The main parameters of technic characteristics are summarized in Table 2.

TABLE II THE KEY ASSUMPTIONS

Name of parameter; Unit of measurement	Value
Minnimal water level of Kruonis PSHPP reservoir (Hmin),m	5
Maximal water level of Kruonis PSHPP reservoir (Hmax),m	13.5
Initial water level of Kruonis PSHPP reservoir ($\boldsymbol{H_{init}}$), m	13.5
Final water level of Kruonis PSHPP reservoir ($\boldsymbol{H_{final}}$), m	13.5
The unit's operational range in generator mode ($\boldsymbol{P^t_{gen}}$), MW	225
The unit's operational range in pump mode ($\boldsymbol{P^t_{gen}}$), MW	220

Forecasting of state variables

When implementing (2), (3) or (4) the greatest difficulties are associated with the need to forecast state variables for the entire planning period, which, in the tasks of economic justification of power plants, is tens of years. The problem is complicated by the need for prediction market prices and solar generation with high resolution (one hour or less). One of the commonly used methods to overcome these difficulties is the decomposition of time series into a set of components that can be associated to different types of temporal variations. The original time series is often split into 3 mutually independent from one another component series [21]:

$$X_t = T_r + S_t + E_t \tag{7}$$

where X_t denotes the observed series; T_r — the long-term trend; S_t describes the seasonality and E_t the noise. Unfortunately, in the problem under consideration, the reliable time series of historical market price records are too short to identify a trend. To overcome this problem, we assume that long-term trends in processes can be described by changes in yearly average parameters. This assumption makes it possible to use models which have been proposed for yearly average market price trend estimation [22]. Following, we will use two types of long-term forecasts: obtained on the basis of using a version of a commercial modeling system called the EFI Multi-area power planning model (EMPS model), also known as Samkjøringsmodellen or Power Market Analyzer [22]; borrowed from the European Union Outlook 2050 energy price scenario, released by Energy Brainpool (June 2017) [23]. The used results of the average annual price prediction are presented in Figure 1.

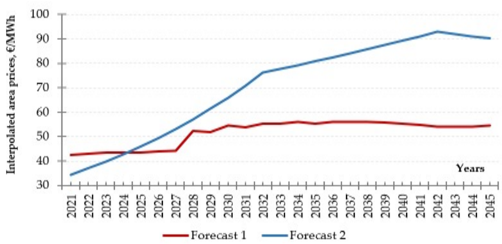

Figure 1. Annual average electricity prices, using Forecast 1 and Forecast 2

Forecasting using the decomposition of time series (7) includes the following steps. The assessment of the average annual price in time series of the base year is being replaced by estimates of the average annual price of future years [24]. The transformed time series is used to evaluate economic indicators. It is important to note that the transformed time series contains seasonality S_t and the noise E_t. To predict the production of solar energy, we use the well-known approach [25] based on the lagging time series of production records of neighboring photovoltaic plants. For this, during 2018, records of the generation of 20 distributed PV stations with a total capacity of 60 kW were collected [25]. The generation volume of a powerful floating station is estimated by the introduction of a scaling factor. Long-term forecasts are based on a naive approach, i.e. we assume that annual generation will be repeated every year of the planning period. In order to simplify, we decompose the problem, i.e. the planning period is divided into years, and years into weeks.

Weekly income maximization and distribution of winnings

The results of maximizing the weekly incomes of a hybrid power plant are shown in Figure 2. A graph of incomes' changes for both players (Kruonis FPV-PSHPP (green curve) and TSO (dark orange curve)), as well coalition incomes are displayed depending on the value of the variable P_{tran}. There are two peculiar points on the Figure 2: the first (point ***A***) corresponds to the average European UTT (P_{tran}= 8.23 €/MWh), and the second (point ***B***) to the zero tariff i.e. P_{tran}= 0.00 €/MWh. Comparison of total profits allows us to conclude that the choice of the second point is rational, since it provides an income increasing by more than ten percent. However, the zero tariff robs TSO` revenue. This injustice is eliminated using Shapley's distribution. Half of the extra profit (91 127 €) is added to the amounts that the players would receive if they choose operating regime corresponding to the first point.

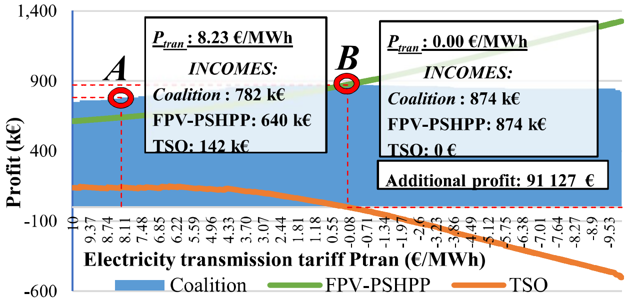

Figure 2. Income dependence on the electricity transmission tariff for time horizon 31/07/2018-06/08/2018

Optimal schedule of Kruonis FPV-PSHPP at two values of electricity transmission tariff is outlined in Figure 3.

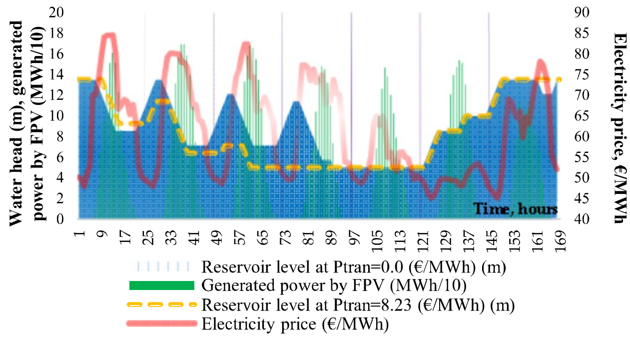

Figure 3. KRUONIS PSHPP and FPV joint operation upon P_{tran} = 0.00 (EUR/MWh) for 31/07/2018-06/08/2018

Accordingly to the Figure 3 data, weekly capacities produced by Kruonis FPV-PSHPP at P_{tran}=0.0 €/MWh and P_{tran}=8.23 €/MWh differ approximately twice and are 30,600 MWh and 14,400 MWh respectively.

Variability of market prices and energy generated by solar panels vary over time causes changes in operating modes and incomes. The possible range of mentioned fluctuations are presented in Table 3, which outlines the results obtained for four weeks, representing all seasons of the year.

TABLE III INCOMES OF THE PLAYERS AND COALITION

Season/period (2018 year)	**I_{FPV}, k€**	**$I_{FPV-PSHPP}$, k€**	**I_{TSO}, k€**	**$I_{FPV-PSHPP+TSO}$, k€**	**P_{trans}, €/MWh**
Winter /31/07 -06/08	22	226 (**594**)	263 (7)	489 (**601**), Δ= **112**	0.13
Spring /31/07 -06/08	280	356 (**473**)	103 (**-3**)	459 (**470**), Δ= **11**	0.09
Summer /31/07 -06/08	564	640 (**873**)	142 (**0**)	782 (**873**), Δ= **91**	0.00
Autumn /31/07 -06/08	272	510 (**876**)	280 (**-16**)	790 (**860**), Δ= **70**	0.25

**The table shows the results of optimization for two cases: 1. Use of existing rules (P_{tran}=0.0 €/MWh); 2. Formation of a coalition (the result is given in brackets); 3. symbol Δ in coalition column presents difference between profits of two operational regimes under consideration and is equal to additional profit witch have to be shared between players by Shapley distribution.*

The data of Table 3 show a strong dependence of player income on price fluctuations and taxation rules. The optimal value of tariff P_{trans}, has seasonal pattern, therefore it should be selected for each specific week separately. Ccoalition formation is beneficial for all players and provides a significant increase in their profits.

Profitability assessment of FPV station

To measure profitability, we use net present value (NPV) of a cash flow. Aadditional assumptions were made to evaluate the benefits of building FPV station: the loan interest rate was assumed 2.6% per annum [26]; the discount rate was assumed to be 2.0% per annum. The credit period is assumed to be equal to the equipment service life—25 years. The FPV initial investments are evaluated as follows: the installation cost of PV is taken 880,000 €/MW [27]. In accordance with [2], the installation cost of FPV in average is higher by 10%, then PV installation cost. However, due to the fact that the FPV capacity is enormous (250MW), the bulk purchase reduces the total investments of installing equipment [28].We assume that this decrease is by 30%. As a result, FPV total investments are 169,400,000 €.

We review two examples of NPV evaluation. The first one entails applying Forecast 1 to evaluate the additional profit created by an FPV plant, and the second one – Forecast 2. We consider two examples of NPV assessment. The first one shows the case of a lack of subsidies supporting renewable energy. The second example assumes the availability of subsidies in the amount of 95,750,000 € [29]. The Figure 4 presents the annual additional profits, using 2 different electricity price forecasts. As we can see, the additional profit for different forecasts is significantly different. This is enabled by diverse average growth rates (Figure 1).

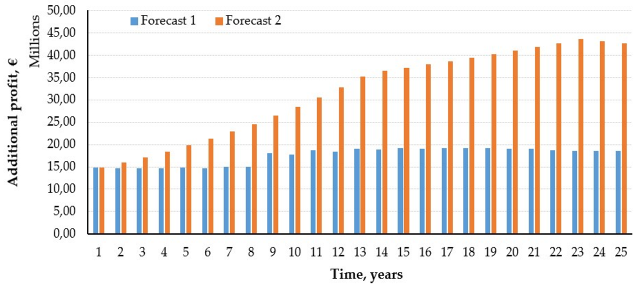

Figure 4. Additional profit created by FPV station

We can conclude that using price forecasts, you need to be careful. Since this significantly affects the final result of the task.

Figure 5 represents the NPV curves (without subsidies). The PP of FPV investment for 1st Scenario is 13 years, however for the 2nd Scenario - more than 25 years that is unacceptable. Applying subsidies, the situation changes significantly. For the 1st Scenario PP of FPV is only 6, but for the 2nd Scenario – 8 years.

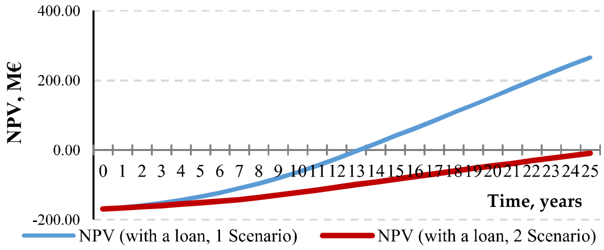

Figure 5. Resulting NPV without subsidies

Despite the need for multiple use of the maximisation procedure, the possibility of using integer linear programming allows us to solve the problem of distributing additional profit for an acceptable time. For the mentioned optimisation purpose the computing environment for engineers and scientists was applied, namely MATLAB 2018b` release with appropriate optimisation toolbox and respective mixed-integer linear programming (MILP) optimisation function – “intlinprog” [30]. Moreover all calculations have been realized on the process i5-4210M CPU@ 2.60GHz with 8.00 GB RAM where one optimisation procedure takes approximately 16 seconds.

IV. CONCLUSIONS

The choice of the operating mode of a hybrid power plant can be made on the basis of the formulation and solution of a complex optimization problem that requires prediction of the processes of price changes and solar generation for a long period and with high resolution. Long-term price prediction can be implemented based on the use of external predictions of changes in average annual prices and the adoption of a hypothesis about the invariance of seasonal and random components during the planning period. A coordinated and beneficial decision for all players can be made using the Shapley approach. The PP of a FPV station, depending on the scenario of price increases and applying or not applying subsidies, ranges from 6 to 25 years, which may be acceptable to investors.

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